SIMULATION OF MICRO- AND MILLI-SECOND SPILL STRUCTURE

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Motivation

- Strong focus on slow extraction, in particular spill structure, since beginning of last year.
  $\rightarrow$ Previous slow extraction workshop in Darmstadt in June 2016.
- Slow extraction experiment at COSY
  - Plan started at beginning of this year, measurement will be in December.
  - Focus on quadrupole extraction, stochastic extraction, and combination of both.
- Slow extraction project proposal funded by BMBF (German federal ministry for education and research). Goal: improving spill quality of GSI synchrotrons, main focus on SIS-100.
  - Submission: November 2017, applicant: O. Boine-Frankenheim.
  - Collaboration with GSI beam diagnostics (P. Forck) and CERN (B. Goddard).
  - Two parts: measurements including detector development and simulation including code and model development.
  - Measurements at existing rings: SIS-18 at GSI and within agreements on beam time with further facilities: HIT / MIT, COSY.

Motivation

Motivation for starting simulation work on spill structure in first half of this year: Results of spill measurements at GSI heavy ion synchrotron SIS-18.

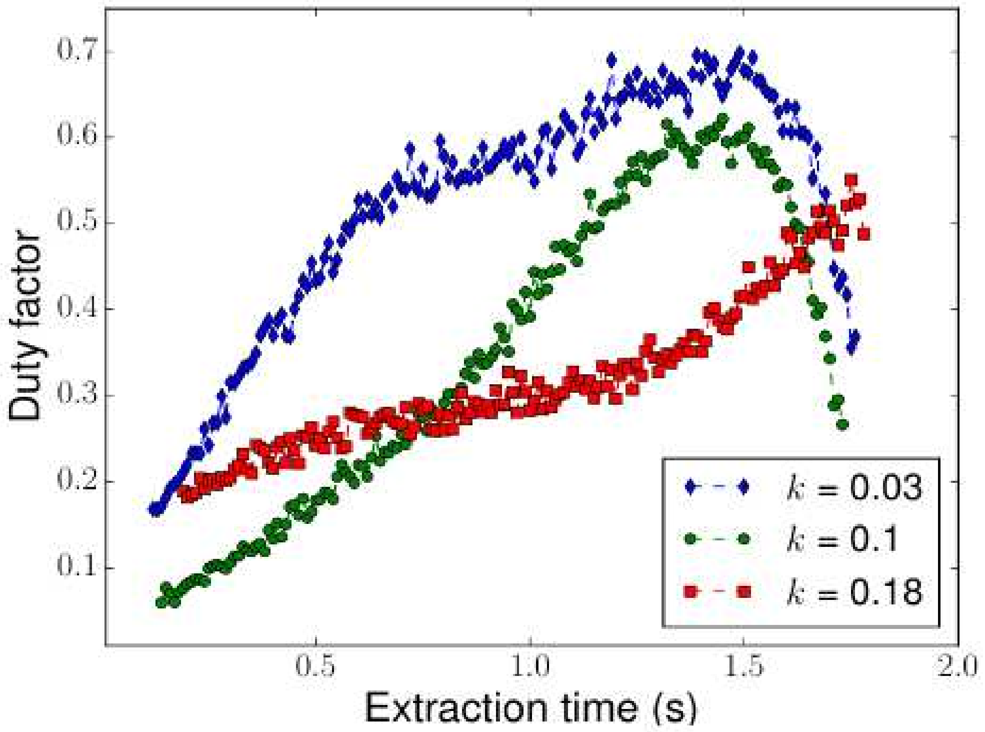
- Measurements done last year by GSI Beam Diagnostics: R. Singh, P. Forck, P. Kowina, in collaboration with P. Schmid, A. Stafiniak, H. Welker *et al.*
- Measurements for different methods and conditions
  - quadrupole extraction and dependence on
    extraction length, chromaticity, momentum spread, sextupole strength.
  - RF-KO extraction and dependence on excitation strength.
- Strongest effect found: dependence of quadrupole extraction on sextupole strength.
  $\rightarrow$ Chosen for beginning of simulations, results presented in this talk.

Experimental results

- Resonant extraction with quadrupoles in SIS-18, different sextupole strengths applied:

$$(k_2L)_a = (0.03, 0.10, 0.18)\ \mathrm{m}^{-2}$$

- Characterisation of spill by duty factor $F = F(t)$, spill duration in figure: $t_{spill} = 2$ s.



Courtesy: R. Singh *et al.*

$$F = \frac{\langle N \rangle^2}{\langle N^2 \rangle},$$

$\langle \ldots \rangle$ means average of short bins $(10\ \mu\mathrm{s})$ in long bins $(10\ \mathrm{ms})$.

Observations:

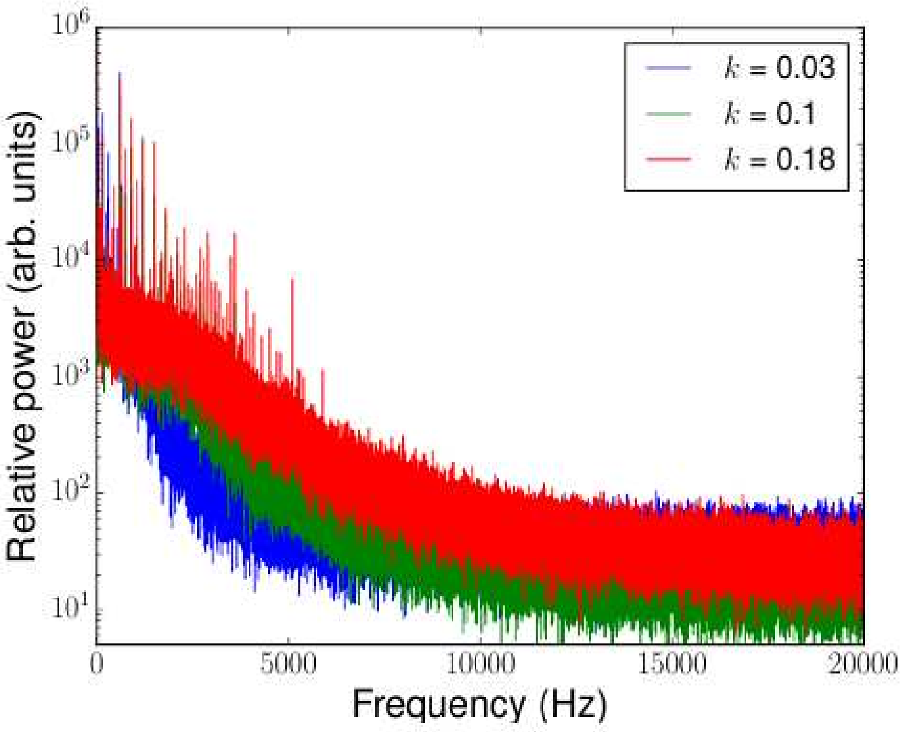
- Generally larger duty factor denoting less impact of field ripple for weaker sextupoles.
- F increases with time.

Experimental results

- Resonant extraction with quadrupoles with different sextupole strengths applied:

$$(k_2L)_a = (0.03, 0.10, 0.18)\ \mathrm{m}^{-2}$$

- Characterisation of spill by spectrum:



Courtesy: R. Singh *et al.*

- Spectra drop at "limiting" frequencies: $f_{lim} \approx 5$ kHz.
- Limiting frequency lower for weaker sextupoles.

Simulation conditions

Simulation of slow extraction by shifting tune into third integer resonance with quadrupoles.

- Thin lens tracking simulation for SIS-18 lattice without any errors using MAD-X.
- Resonance at $Q_x = 4.33333$.
- For simplicity linear change of tune in time.
- Choose $E = 400\ \mathrm{MeV/u}$ $\rightarrow$ resulting revolution time: $t_{rev} = 1.01\ \mu\mathrm{s}$.
- Simulation time interval:
  $t_{sim} = 5 \cdot 10^5\ \mathrm{rev} = 0.505\ \mathrm{s}$ in simulations vs. $t_{meas} = 2\ \mathrm{s}$ in measurements.
- Particle number:
  $N_p = 10^5$ in simulations vs. $N_p \sim 10^6$ in measurements.

Field ripple signal

- Ripple only in defocusing quadrupoles, apply two kinds:
  - Sum of five sinusoidal signals of same amplitude with $f_r = (0.6,\ 1.2,\ 1.8,\ 2.4,\ 3.0)$ kHz:

$$\Delta(k_2L)_{tot}(t) = \frac{1}{\sqrt{5}} \sum_{f_r} \Delta(k_2L)_{f_r}(t).$$

  - Band limited noise signal with $f_r \in [0, 10]$ kHz.
  - Relative amplitude corresponds to

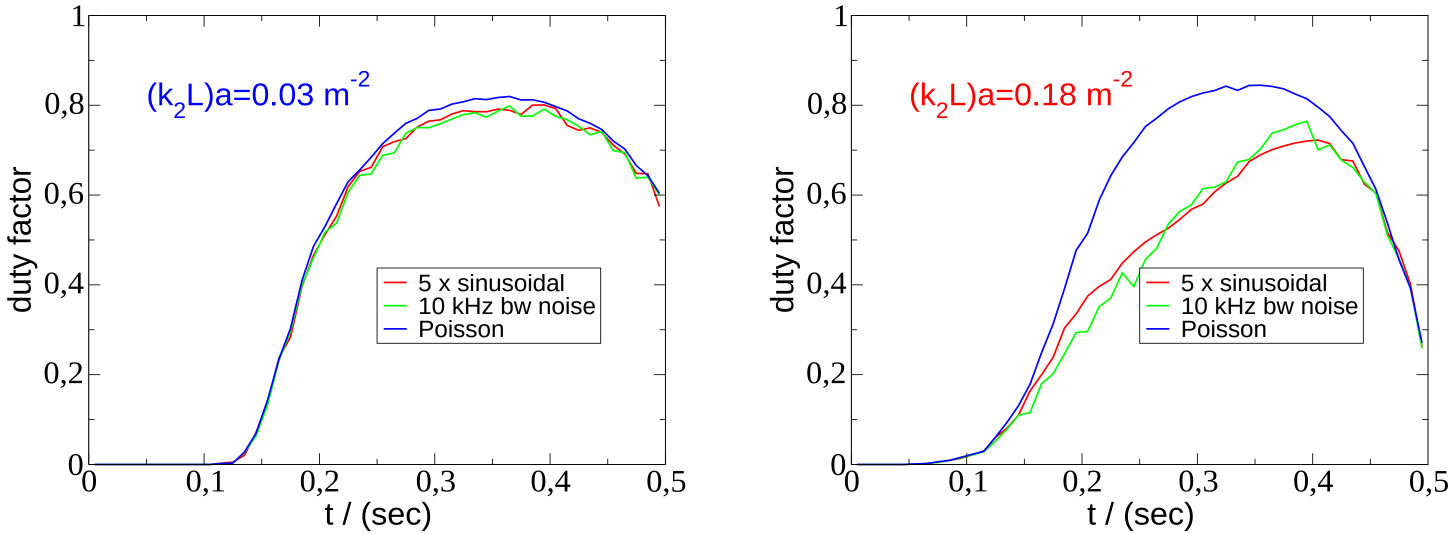
$$\left| \frac{\Delta(k_2L)_a}{k_2L} \right| = 2 \cdot 10^{-6}.$$

- Sextupole amplitudes and corresponding initial horizontal tunes:

  Apply only lowest and highest sextupole strengths used in experiments. Put initial horizontal tunes as close as possible to resonance while no particles lost with static lattice.

$$(k_2L)_a = 0.03\ \mathrm{m}^{-2} \ :\ Q_{x,ini} = 4.327$$
$$(k_2L)_a = 0.18\ \mathrm{m}^{-2} \ :\ Q_{x,ini} = 4.318$$

Duty factor



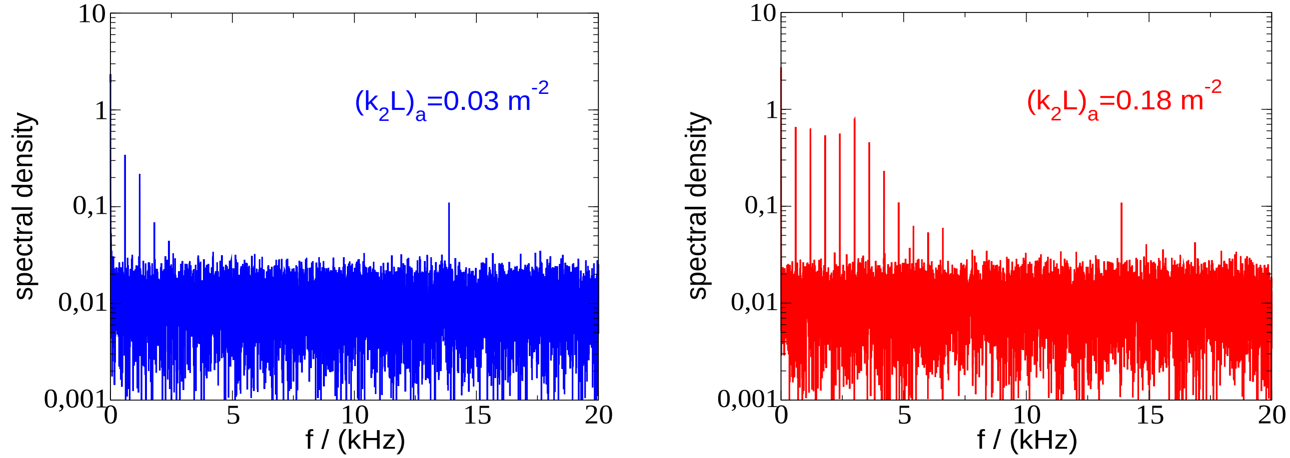
Upper limit given by Poisson duty factor: $F_{Poisson} = \dfrac{\langle N \rangle}{\langle N \rangle + 1}$

Results:

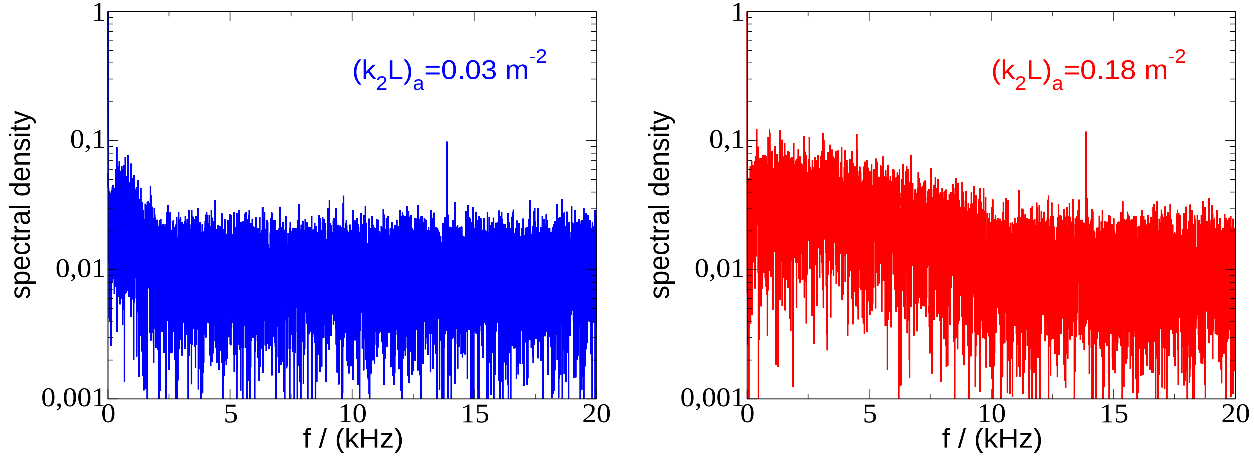
- Effect low. On the other hand ripple only in defocusing quadrupoles and ripple amplitude underestimated due to misunderstanding.
- Reproduction of experimental findings:
  higher impact of ripple for higher sextupole strength and increase of duty factor in time.

Spill frequency spectra

Sum of five sinusoidal signals, maximum excitation frequency $f_{max} = 3$ kHz



Band limited noise signal, maximum excitation frequency $f_{max} = 10$ kHz



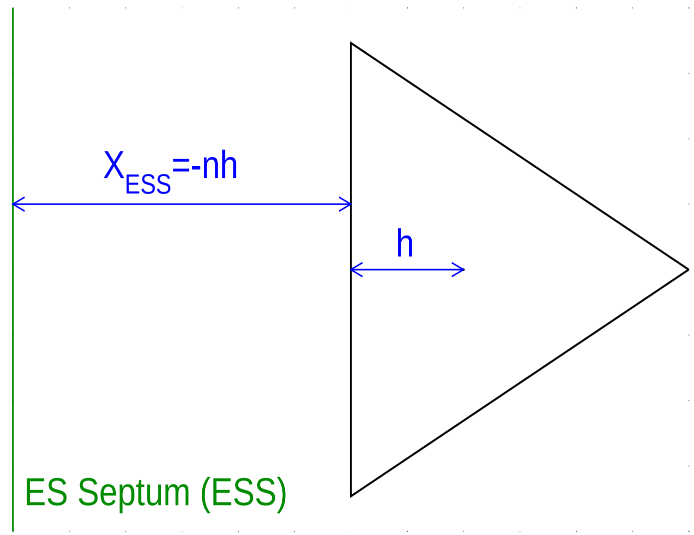
Limiting frequency of spectra $f_{lim} \approx 5$ kHz, lower for weaker sextupoles.

Spill structure and transit time

Idea: Spill and spectra are time dependent due to time dependent spread of transit time washing out high frequency spill structures.

Transit time: formula for transit from corner of stable phase space area to ES septum with changing tune (Equation (4.17) in PIMMS report):

$$T_{transit} = \frac{1}{\varepsilon\sqrt{3}} \ln \left| \frac{n}{n+3} \frac{3}{\frac{\dot{\varepsilon}}{\varepsilon} - \frac{\dot{\varepsilon}}{\sqrt{3}\varepsilon^2}} \right|,$$



where $\varepsilon = 6\pi|Q_x - Q_{x,res}|$ and $n = -\frac{X_{ESS}}{h}$

with $h = \frac{2}{3}\left|\frac{\varepsilon}{S}\right|$ and virtual sextupole strength S.

Q_x and, hence, ε and n are functions of δ and time, expected consequences:
Occurrence of spread of $T_{transit}$ and $T_{transit}$ and its spread are functions of time .

Distribution of Transit time $T_{transit}$ due to momentum spread.

Assume for simplicity Gaussian distribution

$$f(T_{transit}) = \frac{1}{\sqrt{2\pi}\sigma_T}\, \mathrm{e}^{-\frac{(T_{transit}-T_{mean})^2}{2\sigma_T^2}}$$

- Mean value:

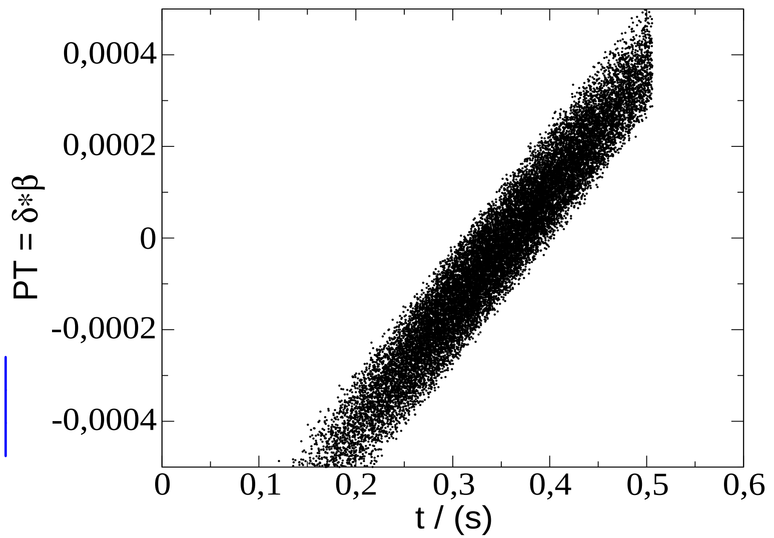
$$T_{mean} = T_{transit}(\delta_{mean})$$

- RMS width:

$$\sigma_T = \frac{1}{2}\left|T_{transit}(\delta_{mean}+\delta_{rms}) - T_{transit}(\delta_{mean}-\delta_{rms})\right|$$

- δ_{rms} determined in $10\ \mathrm{ms}$ intervals and averaged.

Momentum deviations of extracted particles



Spill structure and transit time

Resulting spread of transit time difference

- RMS spread $\sigma_{\Delta T}$:

$$\sigma_{\Delta T} = \left[\int \mathrm{d}T_1 \; f(T_1) \int \mathrm{d}T_2 \; f(T_2) \; (T_1 - T_2)^2 \right]^{1/2} = \sqrt{2}\, \sigma_T$$

  is measure for shortest time structure remaining during transit.

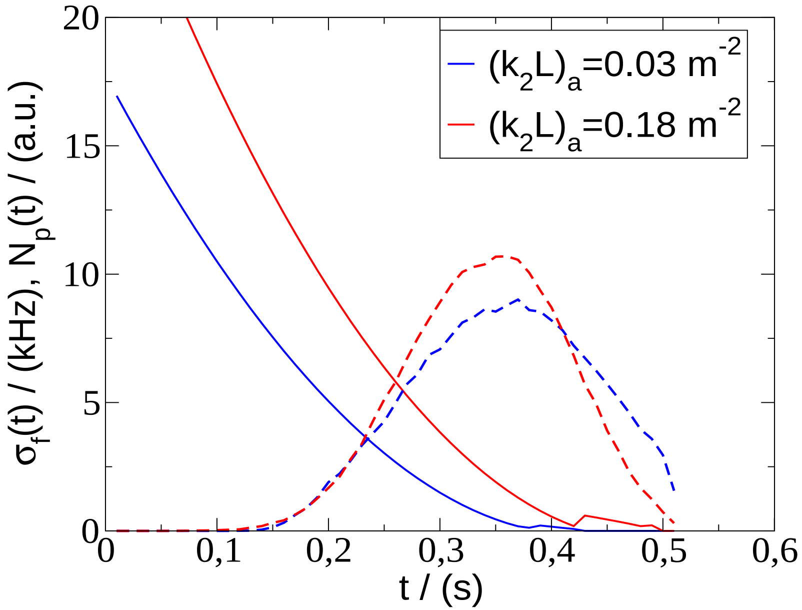
- Resulting RMS frequency spread from Fourier transform

$$\sigma_f = \frac{1}{2\pi\sigma_{\Delta T}},$$

  is measure for the highest frequency which can be resolved after transit.

Spill structure and transit time

$N_p(t)$ and $\sigma_f(t)$



Average: $\langle\sigma_f\rangle = \dfrac{\int \mathrm{dt}\ \sigma_f(t) N_p(t)}{\int \mathrm{dt}\ N_p(t)}$

Frequency limits:

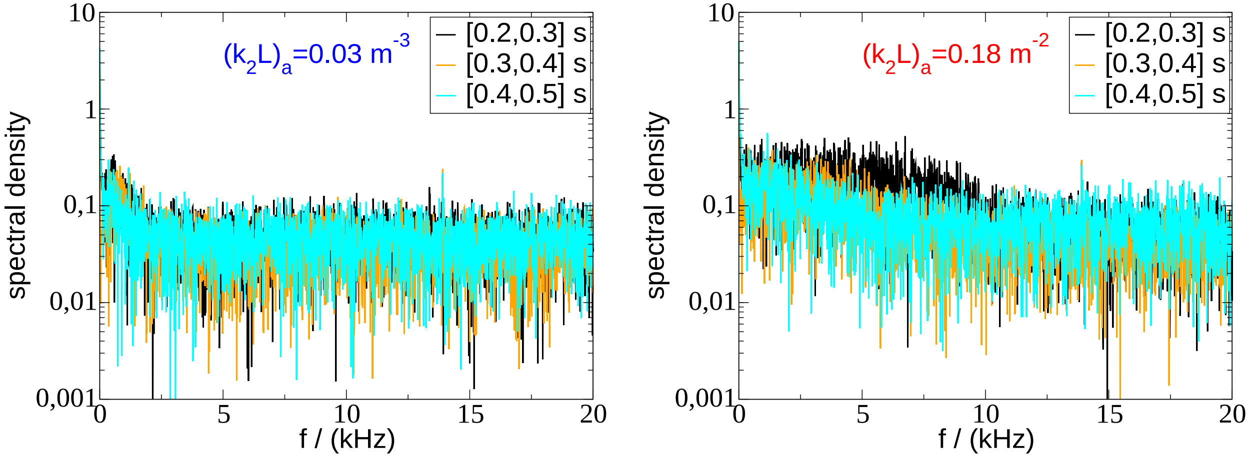
$(k_2L)_a$	f_{lim}, simulation band limited noise	$\langle\sigma_f\rangle$
$0.03\ \mathrm{m}^{-2}$	$2.5\ \mathrm{kHz}$	$1\ \mathrm{kHz}$
$0.18\ \mathrm{m}^{-2}$	$10\ \mathrm{kHz}$	$2.9\ \mathrm{kHz}$

- σ_f unrealistically small for Q_x near resonance.
  $\rightarrow$ Possible reason: transit time formula not valid there.
- No quantitative agreement found. Model is simplified and at least ordering is reproduced.
- Nevertheless, σ_f decreased during extraction which would provide explanation for increase of duty factor. $\rightarrow$ Spectra should be time dependent, talk of P. Forck.

Spill frequency spectra, time dependent

1. Split spills in three time intervals: $[0.2, 0.3]$ s, $[0.3, 0.4]$ s, $[0.4, 0.5]$ s.
2. Apply Fourier transform to parts of spills.

Band limited noise signal, maximum excitation frequency $f_{lim} = 10$ kHz



- Three curves in each figure normalised to same values at $f = 0$.
- Weak sextupoles, $(k_2L)_a = 0.03\ \mathrm{m}^{-2}$: basically, no change in time.
- Strong sextupoles, $(k_2L)_a = 0.18\ \mathrm{m}^{-2}$: Frequency limit decreases in time, i. e. higher frequency components disappear.

Summary and discussion

- Simulations done for conditions not totally different from experimental conditions: time interval: $t_{spill} : 0.5\ \mathrm{s}$ vs. $2\ \mathrm{s}$ and extraction rate: $N_{spill}/t_{spill} : 2 \cdot 10^5/\mathrm{s}$ vs. $10^6/\mathrm{s}$.
- Observations on duty factor and spill spectra qualitatively reproduced with simulations:
  - Dependence of duty factor on sextupole strengths and time.
  - Limiting frequencies of spectra lower for weaker sextupoles and decreasing in time, if sextupoles are sufficiently strong.
- Simple model based on determination of spread of transit time using analytic formula: Suggests that dependencies of duty factor and spectra on sextupole strengths and time arise from different spreads of transit times of particles.
- Open point:
  Is really sextupole strength important variable or difference between machine and resonance tunes? Possible clarification with simulating extraction with constant tune and increasing sextupole strength.

Next steps

- Completion of current simulation model of quadrupole extraction in SIS-18: inclusion of ripple in other magnets and application of realistic ripple amplitudes.
- Modelling extraction of bunches.
- Modelling other slow extraction techniques:
  1. RF-KO extraction:
     investigation of used and foreseen scenarios as well as of different RF spectra.
  2. Stochastic extraction:
     Problem: Lattice with cavity. Results in artificial particle loss in MAD-X simulations.
     $\rightarrow$ Use simplified tracking model?

Acknowledgement

Thanks to my colleagues P. Forck and R. Singh for data and discussions.